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Advanced High Temperature Structural Seals

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The Boeing Company, Seattle, Washington

November 2000

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FOREWORD

This interim report, prepared by the Boeing Phantom Works organization, is provided under the Structural Technology and Analysis Program (STAP), Advanced High Temperature Structural Seals (Delivery Order No. 0012) contract. The reporting period is 6 May 1999 to 5 November 1999. The U.S. Air Force funding is under Contract No. F33615-95-D-3203. The Program Technical Monitors are Harold Croop from Air Force Flight Dynamics Laboratory and Dr. Bruce Steinetz from NASA Glenn Research Center. Funding for this program originated with NASA under the Bantam launch vehicle program.

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ADVANCED HIGH TEMPERATURE STRUCTURAL SEALS

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SUMMARY

This program addresses the development of high temperature structural seals for control surfaces for a new generation of small reusable launch vehicles. Successful development will contribute significantly to the mission goal of reducing launch cost for small, 200 to 300 pound payloads. Development of high temperature seals is mission enabling. For instance, ineffective control surface seals can result in high temperature (3100° F) flows in the elevon area exceeding structural material limits. Longer sealing life will allow use for many missions before replacement, contributing to the reduction of hardware, operation and launch costs.

During the first phase of this program the existing launch vehicle control surface sealing concepts were reviewed, the aerothermal environment for a high temperature seal design was analyzed and a mock up of an arc-jet test fixture for evaluating seal concepts was fabricated.

INTRODUCTION

This effort provides for the analysis, design, fabrication and testing of advanced structural seal concepts, with emphasis on developing and validating seal concepts incorporating current state of the art materials, not developing new materials. Key to the success of this program will be use of emergent materials in combinations that will result in durable, feasible, and affordable seal designs. At the completion of the program, a matrix of materials and material combinations will have been developed for a range of aerothermal environments for a wide variety of advanced control surface/thermal protection systems and advanced structures. Test article types will include sub-element seals and validation seals. Testing will include thermal and mechanical loading and arc-jet exposures. Aerothermal/structural analysis methods applied early in the program to design the seals will be validated by comparing the predicted and measured seal thermal/structural responses of the validation seals in arc-jet tests.

PROGRAM PLAN

This program consists of a multi-year technical effort, and this interim report covers the first six months of the program. Future reports will cover progress made in subsequent reporting periods. The five principal technical tasks in the program include:

- (1) Determine seal requirements
- (2) Select candidate seal concepts/materials
- (3) Perform thermal/structural analyses
- (4) Test seal concepts under representative conditions using NASA-ARC arc-jet heating facility
- (5) Provide seal designs/databases to vehicle programs for successful implementation and flight.

RESULTS AND DISCUSSION

The requirements for control surface seals for small reusable launch vehicles were established through technical interchange meetings at NASA-JSC (X-38 program), NASA-ARC (Thermal Protection Branch), NASA-KSC (Orbiter experience), Boeing Seal Beach (X-38 program), and Hi-Temp (seal and TPS fabricator). Aerothermal analysis of the seal area has identified the temperature range of the control surface seal area.

Lessons Learned from Orbiter Experience and New Program Plans

The primary difference between the seals for new smaller vehicles and those used on the Orbiter relates to the size and thickness of the wing and control surfaces. The thickness of the Orbiter wing allows the control surface seals to be buried away from the wing-elevon gap, permitting the ultimate pressure seal to be achieved at a relatively low temperature by a flexible polymer rubber strip. The new smaller vehicles will have significantly reduced wing depth, eliminating the thermal drop from the elevon gap to the seal, which is used effectively in the Orbiter. The result is much higher temperatures at the sliding seals, requiring ceramic materials for survivability. A typical double-bulb seal type of construction is shown in figure 1.

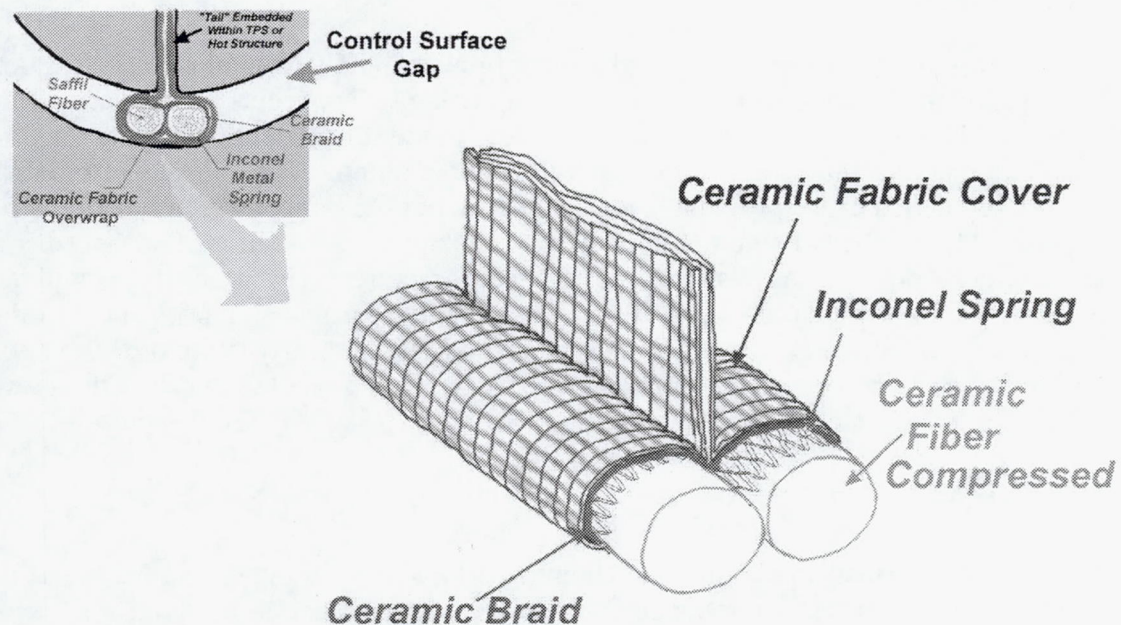


Figure 1 High Temperature Bulb Seal – Wrapped with Ceramic Fabric

Compressible ceramic fiber bulb seals are used in static gap areas on the exterior of the Orbiter, but not in areas exposed to extensive sliding or reciprocating motion. These seals are made from

Nextel™ 312 outer fabric over an Inconel woven spring and ceramic insulation, and have a reusable temperature limit of 1600°F. Similar semi-static seals designed for the X-33 use Nextel™ 440 fabric with stiffer knitted Inconel springs and have an upper use temperature of about 2000°F. Spring-loaded silicide-coated niobium seals are used at the ends of Orbiter control surfaces, but due to cost, weight and rigidity are not suitable for use on spanwise seals.

Dellacorte and Steinetz¹ published data on testing all-ceramic braided rope seals, but very little data exists on sliding wear behavior of ceramic fiber covered bulb seals. Anecdotal evidence indicates that harness satin weaves provide better sliding wear than plain weave -- providing that sliding direction is parallel to face fibers, although current seal fabricators may not differentiate between warp and fill faces when wrapping fabric.

The specific face of the fabric is the surface of the fabric that exposes the floating yarns of the particular fabric direction (denoted by *warp* or *fill*). Figure 2 depicts how the difference in direction may be significant in sliding contact behavior of harness satin weaves. Harness weave fabrics are considered to be better in sliding contact (in the warp direction against the warp face) than other weave types. Sliding contact in a direction 90 degrees to the floating yarns is expected to cause significantly more damage. In figure 2 the most damage prone direction is the fill direction (**B**) with sliding contact against the warp face.

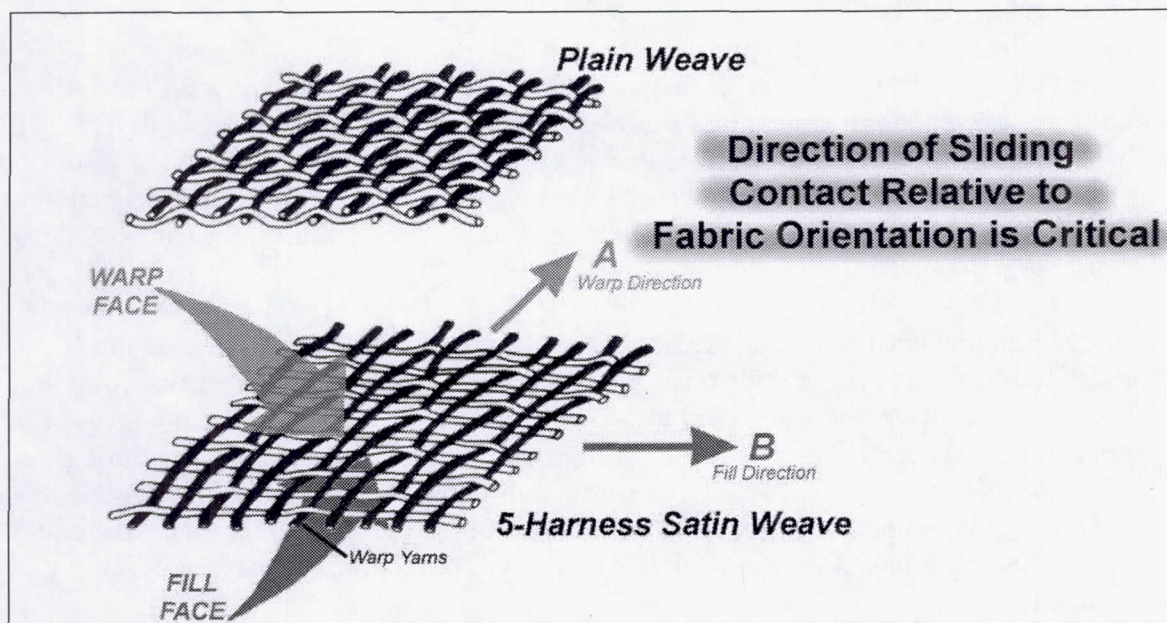


Figure 2 Direction of Sliding Contact Relative to Fabric Orientation

¹ Dellacorte, C. and Steinetz, B.M., "Relative Sliding Durability of Candidate High Temperature Fiber Seal Materials," NASA Technical Memorandum 105806, August, 1992, Lewis Research Center, Cleveland, Ohio

Candidate Seal Concepts and Materials

As our baseline seal candidate we are focusing on a bulb seal as shown in figure 1. This design – whether with one or two “bulbs” – has a wealth of experience on the Shuttle and on other emerging programs such as X-33. Our material choices for initial concepts will be:

Nextel™ 440 for the ceramic fabric wrap.

Nextel™ 440 for the braid over the metal spring and the fiber fill.

Inconel™, multi-wire, metal alloy spring

Saffil™ fiber for the fill material

Design issues with this concept are permeability, abrasion resistance after thermal exposure, resiliency after thermal exposure, and shape retention after thermal exposure. These issues will be explored under the second phase of this project. Approaches for decreased permeability and resiliency may be, respectively, additional ceramic or metallic elements within the “bulb,” and inorganic replacements for the spring element. What may ultimately be required is a ceramic construction for the spring element. This new element would probably be a fine gage ceramic-matrix-composite “spring.” It would allow the seal to retain its shape and resiliency after thermal exposure to temperatures of 2400°F.

Aerothermal Analysis

An aerothermal analysis was performed using an X-38 environment, and a 2-D body-to-flap control surface seal arrangement that was based on one of the X-38 candidate designs. This vehicle and its parameters were selected because they were representative of the types of designs for the new generation, smaller vehicles. The analysis included computed fluid dynamics (CFD) analysis using FLUENT software for 2-D analysis of gas temperatures, pressures, and flow vectors.

Two seal arrangements were analyzed: one with an impermeable seal where no fluid transmission was allowed; and the other with a permeable seal that used a value for permeability comparable to 3-D woven forms used for resin transfer molding analyses. Some degree of permeability will need to be considered for high temperature seals based on ceramic fiber technologies. However, in retrospect the permeability that we selected is probably on the high side, resulting in temperatures for the permeable seal case that are higher than what could be expected. During Phase II the permeability issues will be examined analytically and by experiment.

Figures 3 and 4 summarize the aerothermal analysis and its assumptions.

- 2-D Navier-Stokes analysis using commercial CFD code FLUENT
- Limited computational domain for faster turn-around
- Evaluate effect of seal permeability
- Use CFD results at key trajectory points to scale simpler methods for entire trajectory
- Apply predicted environments to structural thermal analysis to determine seal temperatures

Figure 3 Aerothermal Analysis -- Method Description

- Boundary layer growth upstream of domain neglected
- Steady 2-D flow
- Turbulent boundary layer
- 20 degree bodyflap deflection angle
- Radiation equilibrium surface condition ($\epsilon=0.8$, $F = 0.144$)
- Rectangular shaped seal (to simplify computational grid)
- Porous seal has 10^{-7} ft² permeability

Figure 4 Current Assumptions for Aerothermal Analysis

Figure 5 is a representation of the X-38 vehicle, the location of the body to flap region along with the static pressure contour map for a 20-degree flap angle (with an impermeable seal). This plot is used for illustration purposes because static pressure correlates better than other CFD outputs with the heat transfer and ultimately with the temperatures of the structural components.

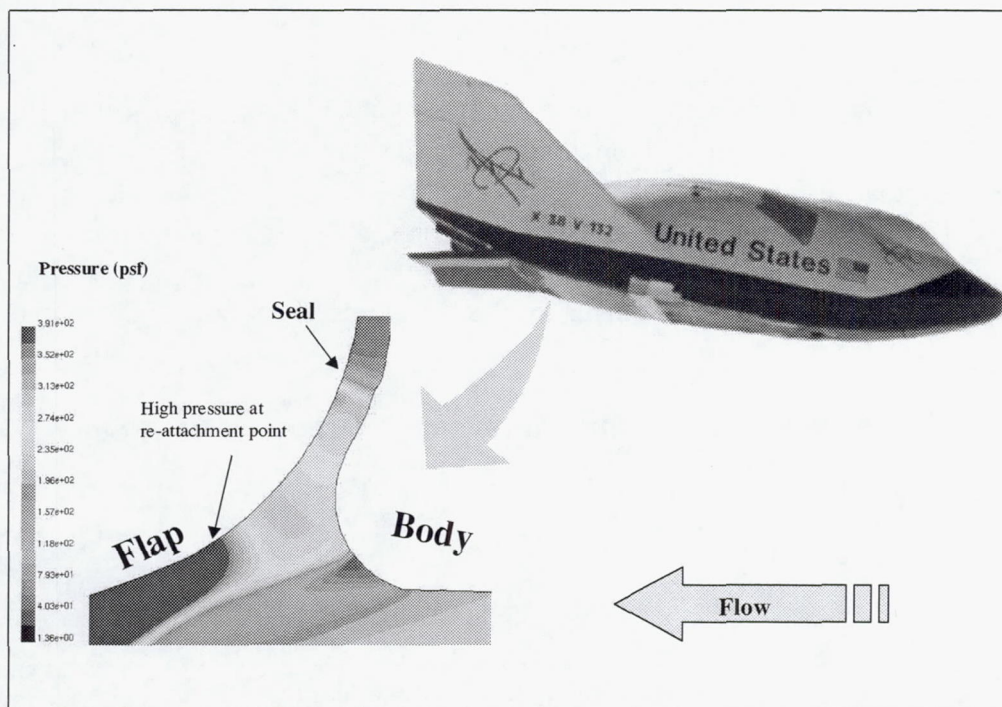


Figure 5 Static Pressure Distribution in Body Flap Gap and Seal Area

Details of the aerothermal analyses are shown graphically in figures 6 through 11 and a brief description follows for each of the figures.

Figure 6 shows the grid used for the localized area of the 2-D representation of the flap-to-body area, including the seal.

Figure 7 shows the flow pathlines for both cases of seal permeability. The extreme degree of permeability for the porous seal does not appreciably affect the flow structure.

Figure 8 of the static pressure distribution indicates that there is not a significant pressure difference at the seal area for the two seal cases.

Figure 9 shows the total temperature distribution in degrees R in the gap and seal region. It should be noted that the total temperature is for the fluid only. The distributions indicate that hot gas will be forced further into the gap; and some amount of hot gas will flow through the permeable seal. Estimates for the heat transfer from the hot gas environment were made based on radiation equilibrium at the surface (an idealized surface assuming emissivity = 0.8; no flow through surfaces; no conduction into structure). Results for these calculations are presented in figure 10 in degrees F and indicate that the seal temperatures are higher, as expected, for the permeable seal. The permeable seal temperatures are in the range of 2500 to 3000°F – for this idealized and worst case condition. In a 2-D transient structural thermal analysis the temperatures are expected to be slightly lower due to conduction of heat into the structure of the body and the

flap. The temperatures provided by the radiation equilibrium temperatures at the surface are a maximum.

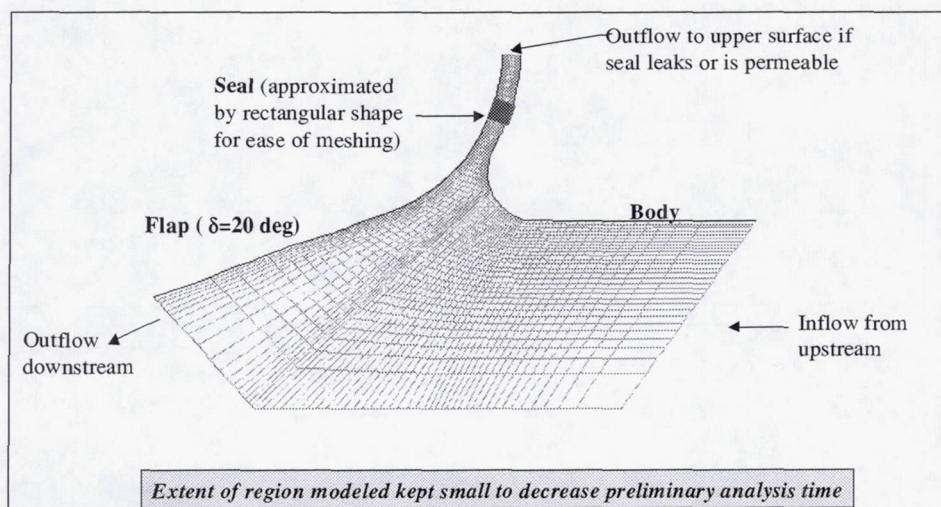


Figure 6 Computational Grid

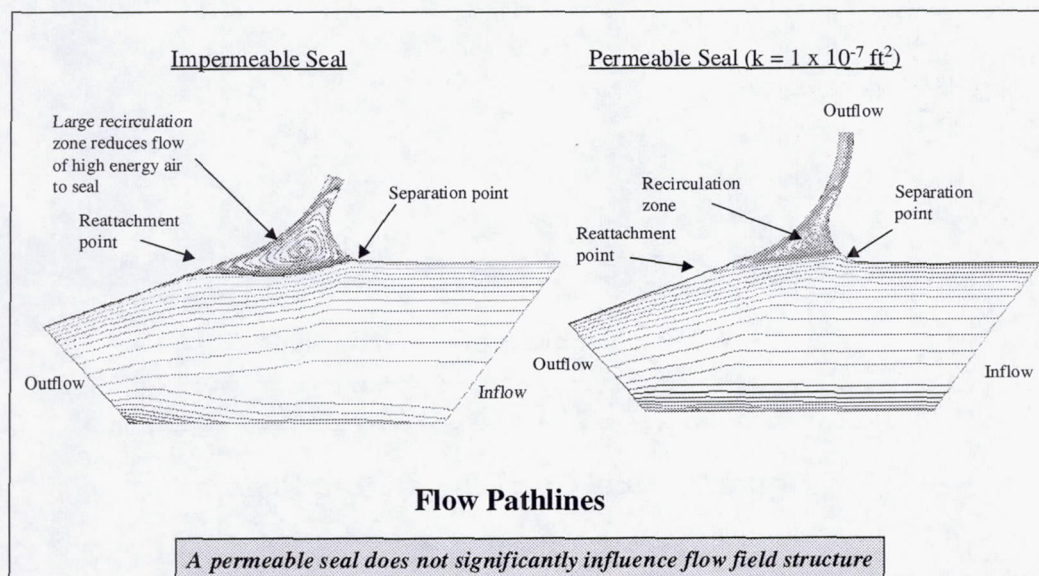


Figure 7 Flow Pathlines

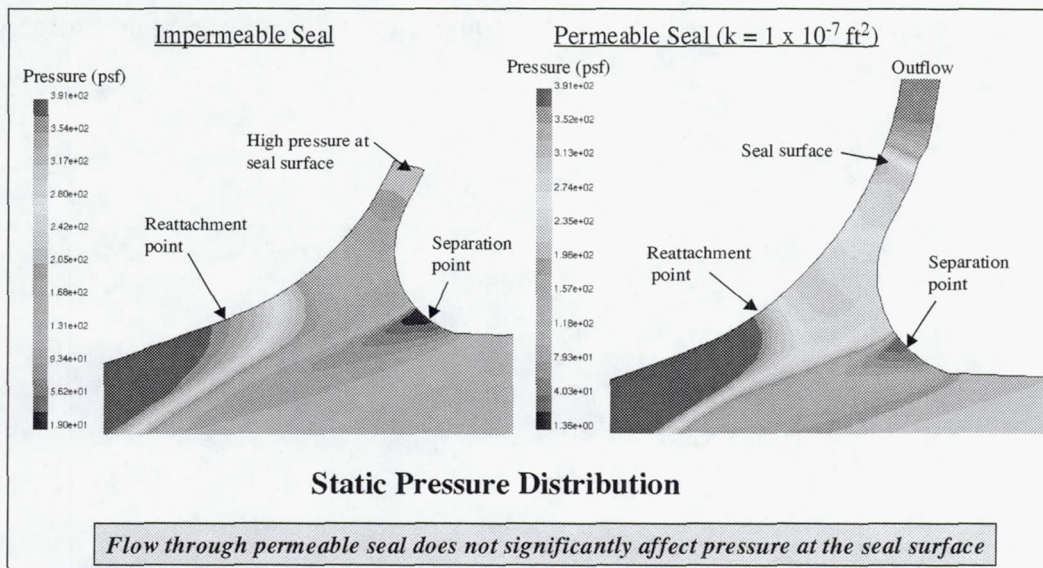


Figure 8 Static Pressure Distribution

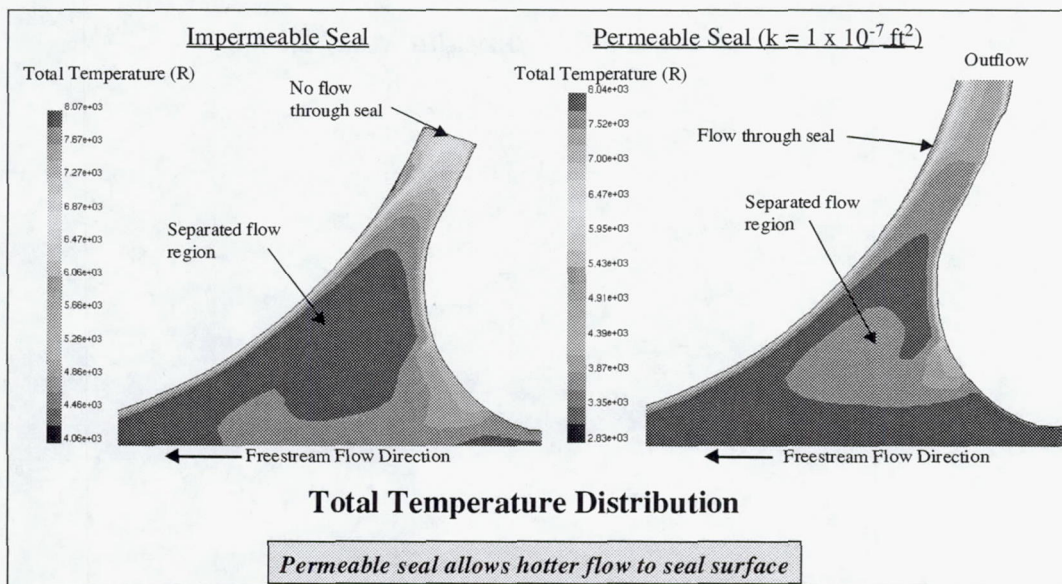


Figure 9 Total Gas Temperature Distribution

Seal Surface Condition (20° flap δ)	Impermeable	Permeable
Radiation Equilibrium Heat Flux (Btu/sq ft-hr)	7000 to 9000	15000 to 30000
Seal permeability significantly increases seal heating.		
Radiation Equilibrium Temperatures (°F)	2000 to 2200	2500 to 3000
High seal permeability significantly increases seal temperatures Note: These radiation equilibrium temperatures are only a rough estimate of actual material temperatures. A transient structural thermal analysis is required to accurately predict seal temperatures.		

Figure 10 Predicted Seal Temperatures

The previous five figures were based on a flap deflection angle of 20°. The maximum radiation equilibrium temperatures from CFD analyses of other flap deflection angles were also determined for the impermeable seal and are plotted in Figure 11. Temperatures of 2500 to 3000°F were calculated for a permeable seal at a deflection angle of 20°. Other deflection angles for the permeable seal will be evaluated over a range of permeability levels at the beginning of the next phase of this work.

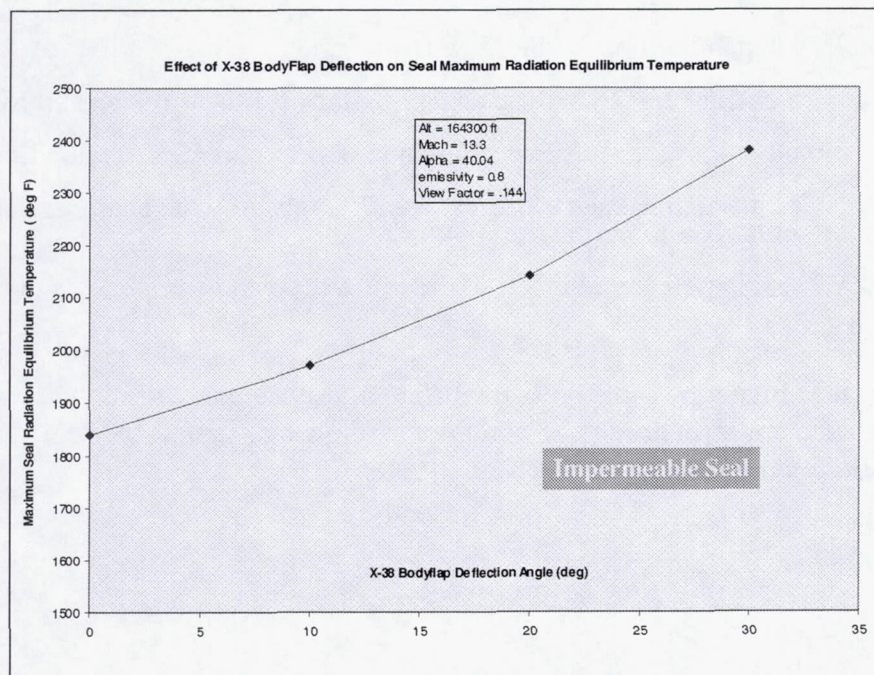


Figure 11 Flap Deflection vs. Seal Maximum Radiation Equilibrium Temperature
 The conclusions of the preliminary aerothermal analysis are listed in Figure 12.

- Preliminary CFD analysis indicates that handbook cavity correlations slightly underpredict the aerothermal environment for deflected flaps.
- High seal permeability (10^{-7} ft²) results in increased aero-heating to the seal. Actual ceramic fiber seals are expected to be considerably less permeable than that in our initial analyses -- resulting in lower temperatures.
- Maximum seal surface temperatures are expected to be in the neighborhood of 2000 to 2200°F for a 20-degree flap deflection for an impermeable seal, and higher for the high permeability seal.
- Seal temperatures increase as body flap deflection angle increases.

Figure 12 Conclusions – Aerothermal Analysis

Arc-Jet Testing -- Test Fixture Mock-Up

Arc-jet testing is a necessary and relevant environment test for seal function. A test fixture was designed in cooperation with the arc-jet staff at NASA-Ames Research Center. The NASA-Ames 20-megawatt Panel Test Facility arc-jet heater was selected for these tests because of:

- Heat flux capability (0.5-75 btu/ft²sec)
- Ability to change the test fixture angle of attack (-4 to +4 degrees) during the run
- Real-time hot-surface video recording and optical pyrometry capabilities
- Ability for mechanical and electrical feedthroughs into the chamber enabling control surface actuation during the run
- Ease of installation and removal of the test fixture and components of the test fixture

Other facilities have higher possible pressure differentials, which may need to be explored on the subelement and element level at specific conditions following satisfactory demonstrations of the high temperature actuated seal designs.

The test article was designed to include the following features:

- Control surface hinge-line seal cavity with replaceable cartridge to quickly and easily change-out candidate seals and seal materials
- Actuated trailing flap to deflect the control surface and assess effects of potential flow ingestion into the control surface hinge-line seal cavity
- Cavity will be well instrumented with probes to measure upstream and downstream pressures and temperatures.
- Test results will be used to validate control surface seal design and aerothermal analyses

We completed a mock-up of the seals test fixture based on dialog between Boeing, GRC, and ARC that incorporated the above features. The mock-up article is shown in figure 13.

The mock-up was evaluated for design applicability and form and function in the NASA-Ames Arc-Jet Panel Test Facility (PTF) in cooperation with ARC personnel. Figures 14 through 16 show the mock-up in the Ames PTF facility. Major issues that were identified during the trials were actuation possibilities, thermocouple and pressure sensor locations, and flap angle constraints. The changes suggested from the dialog between Boeing and ARC will be incorporated in the actual test article.

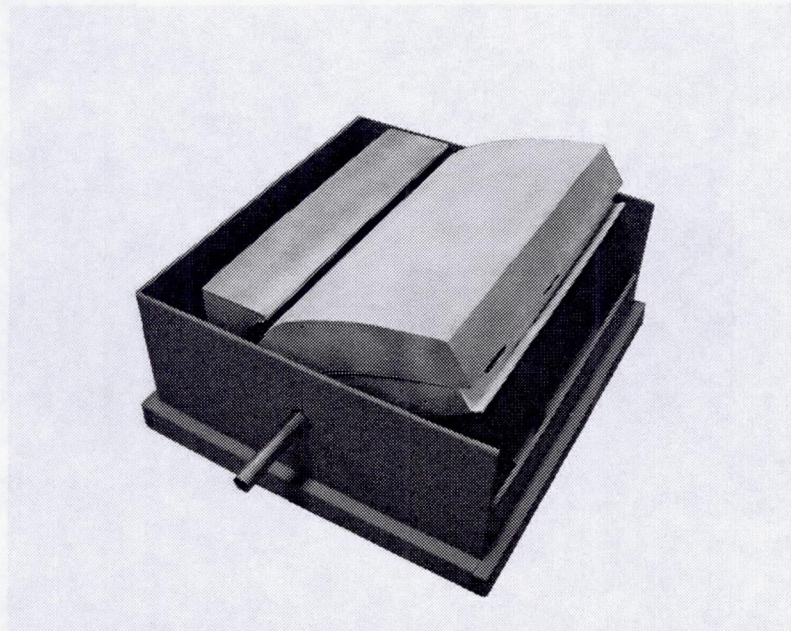


Figure 13 Mock-Up of Arc-Jet Test Fixture for Seals

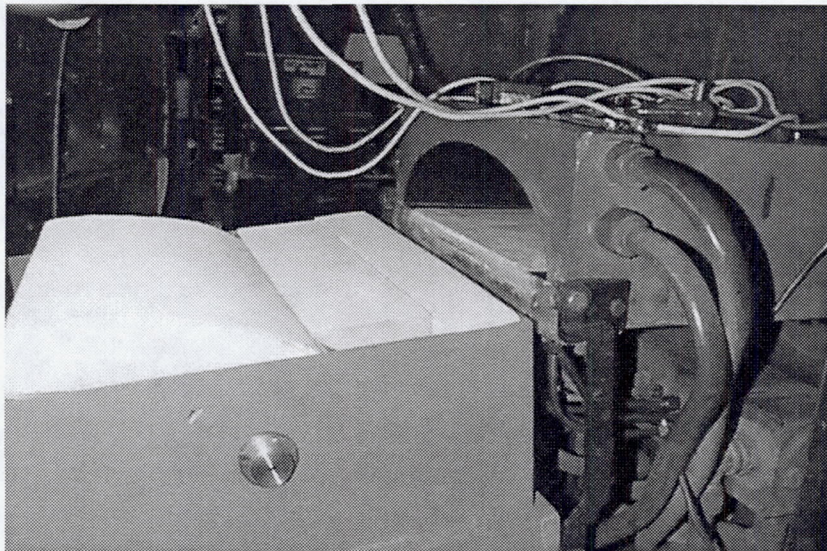


Figure 14 *Test Article Mock-Up in NASA-Ames PTF*

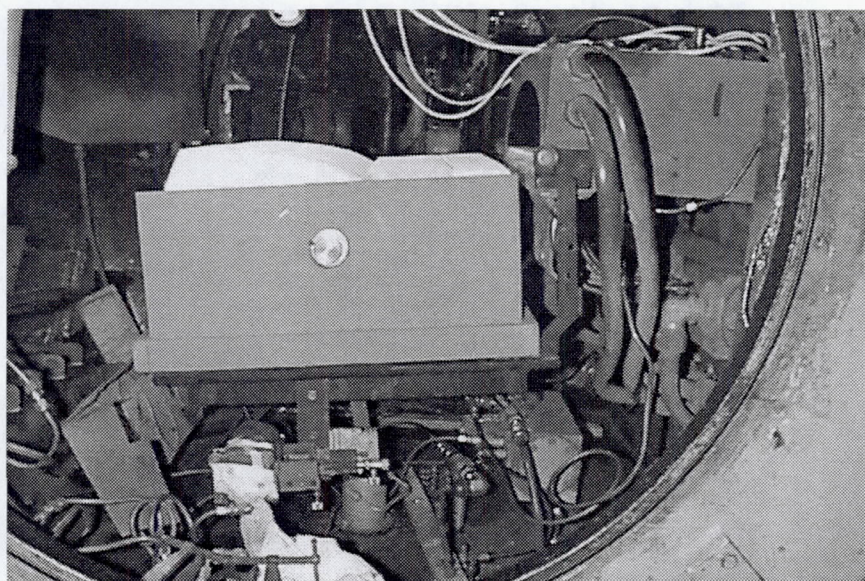


Figure 15 *Test Article Mock-Up in NASA-Ames PTF*

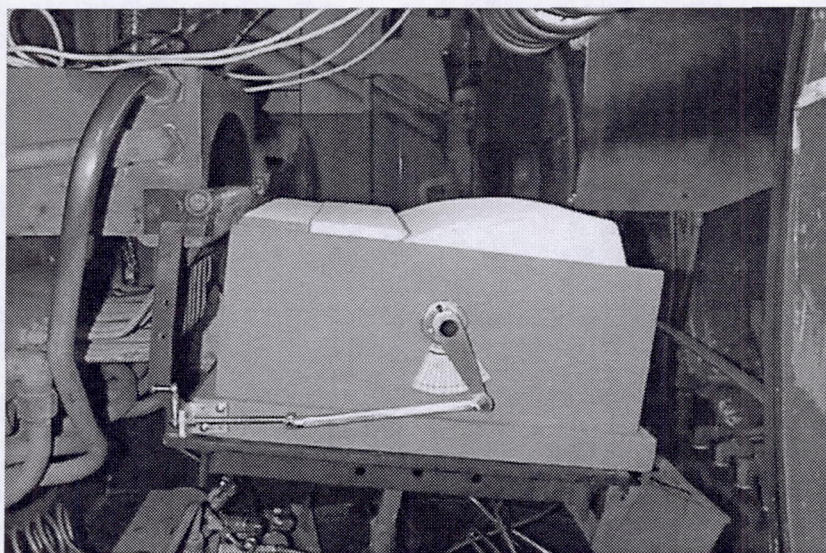


Figure 16 Test Article Mock-Up in NASA-Ames PTF

Planned Continuing Activities:

- Fabricate the Test Fixture
- Design/Fabricate Seals and TPS Components
- Complete Thermal/Structural Analysis

CONCLUSIONS

- Orbiter application experience for seals only extends to 1600°F.
- Sliding wear information at elevated temperatures for ceramic bulb type seals does not exist.
- Small re-entry vehicles will require high temperature capability (2200°F to 2400°F) for acceptable performance.
- Preliminary aerothermal analysis indicates that ceramic seals for X-38 applications appear to require low permeability.
- Metallic springs (as in currently used designs) may be insufficient for necessary resiliency.
- Realistic values for permeability are required for complete analysis.
- A movable test fixture for arc-jet testing of control surface seals has been designed.

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